

MUON COLLIDERS



... a personal request to the Panel to endorse dedicated muon collider R&D

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TOPICS:

- 1) long-term HEP potential of the "discovery lepton"
- 2) energy-frontier future with muon colliders: a plausible scenario
- 3) muon cooling: the signature technology & dominant challenge
- 4) proposed R&D plan for the next 2 years
- 5) in conclusion: requests to Panel

The topics in this talk will be investigated at Snowmass:

see <http://pubweb.bnl.gov/people/bking/Snowmass-mumu>

for parameter sets etc.

Extend the energy frontier!

LONG-TERM POTENTIAL GAINS FROM A 3rd PROJECTILE



Electrons
are too light

Discovery reach
of a few TeV ?



Protons are composite
& strongly interacting

Discovery reach of
some 10's of TeV ?

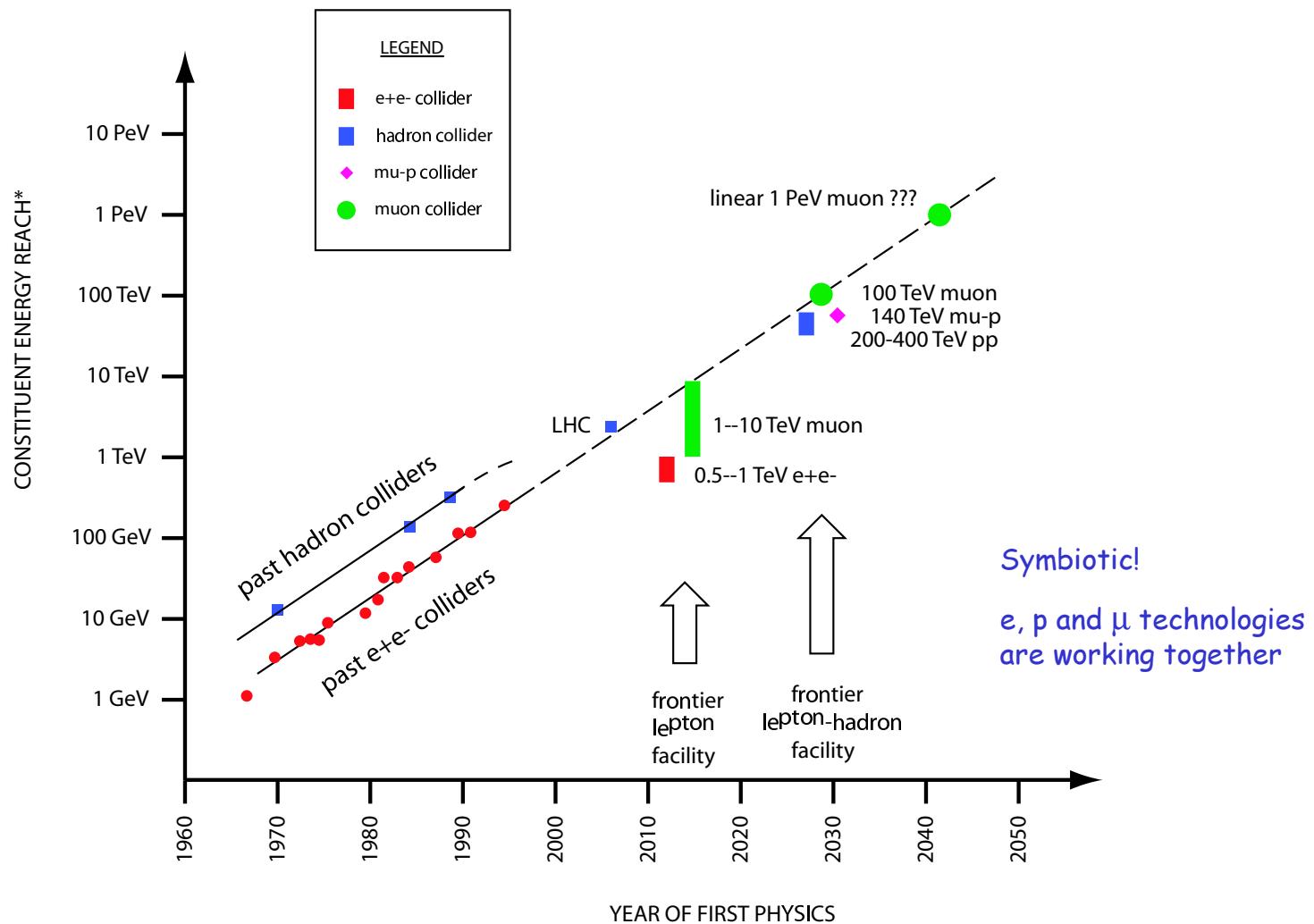


Add Muons,
though unstable

Discovery reach of
~100 TeV (circular)?
~1 PeV (linear)???

Muons have the highest potential discovery reach,
using clean lepton-lepton collisions, so the successful
development of muon collider technology will maximize
the long-term potential of experimental HEP.

"STRAW-MAN" EXAMPLE FOR PLAUSIBLE FUTURE WITH MUON COLLIDERS



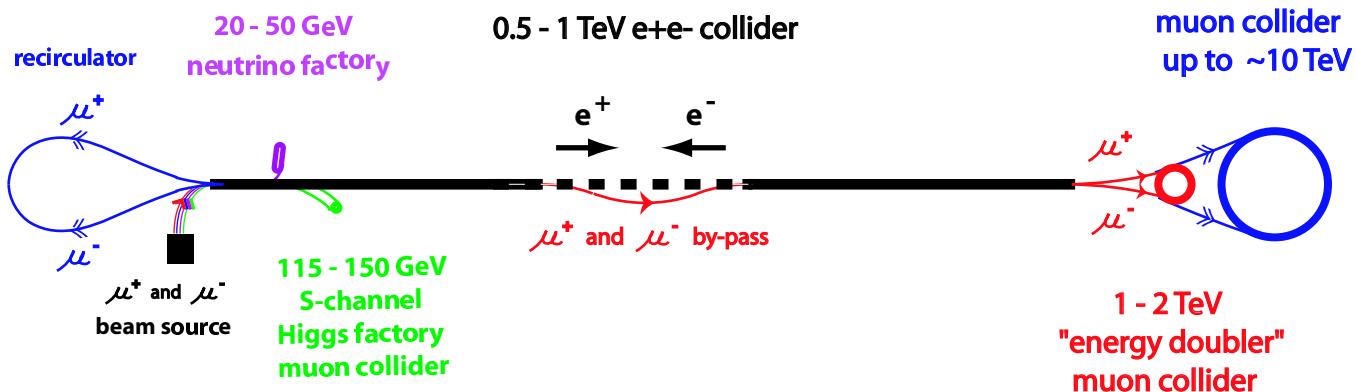
* assume constituent energy reach for hadrons = $1/6 \times$ CoM energy

SYMBIOTIC FACILITY: LINEAR e^+e^- COLLIDER + MUON COLLIDER



First discussed by D. Neuffer, H. Edwards & D. Finley in Proc. Snowmass'96

Works better for larger, superconducting cavities ("TESLA")



CHALLENGES: a) design of (very) high performance muon cooling channel, b) integration into e^+e^- collider design, c) major design constraints & luminosity cap to greatly suppress neutrino radiation
 (worst case $< 10^{-2}$ mSv/y^r $\sim 0.003 \times$ U.S natural bkgrd. rad.)

POTENTIAL: $E_{CoM} \rightarrow 10$ TeV with $\mathcal{L} \sim 1 \times 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$ (+ neutrino, s-channel Higgs factories)

HEP results (LHC, Tevatron, ν physics) will decide the actual add-ons: "Swiss army knife accelerator"

PLAUSIBLE NEW FRONTIER LAB.: VLHC + VLMC

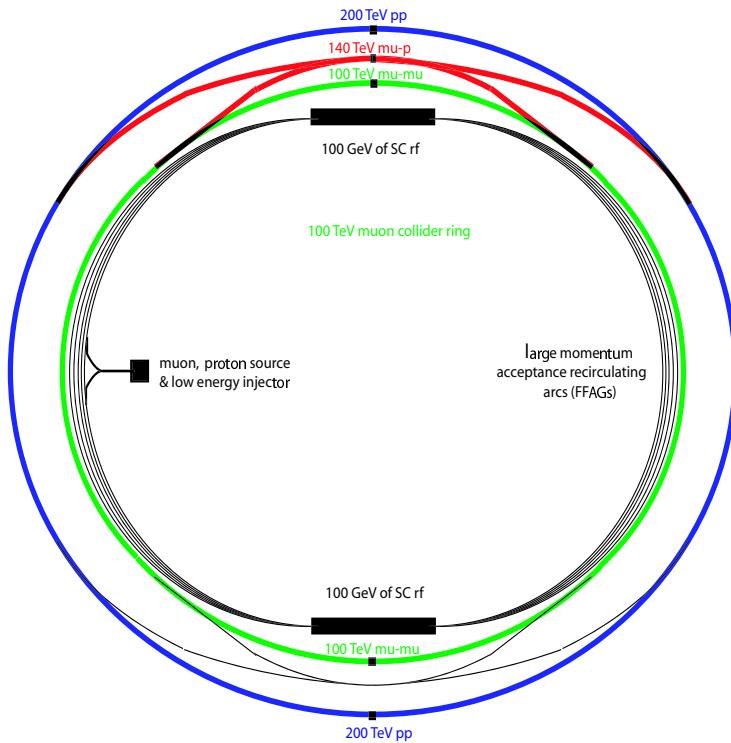


Neutrino radiation => new, very isolated lab. for high luminosity Very Large Muon Collider (VLMC).

On balance, technical difficulties not much worse than for lower energy muon colliders.

(slightly less cooling needed; recent 30 TeV final focus design by Raimondi)

Schematic Layout showing Acceleration,
Muon Collider, Proton Collider & mu-p Collider



VLMC + VLHC symbiosis:

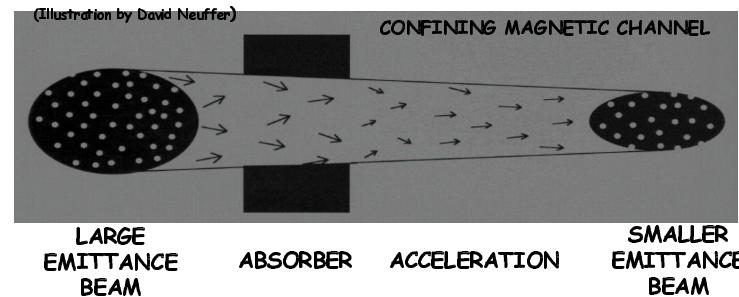
- ✓ common magnet R&D
- ✓ same tunnel, or side-by-side
- ✓ common acceleration to ~50 TeV/beam
 - full energy for muon collider
 - $\sim \frac{1}{2}$ energy for hadron collider
- ✓ mu-p collisions at $E_{\text{com}} \sim 140$ TeV

"IT'S THE COOLING"

μ

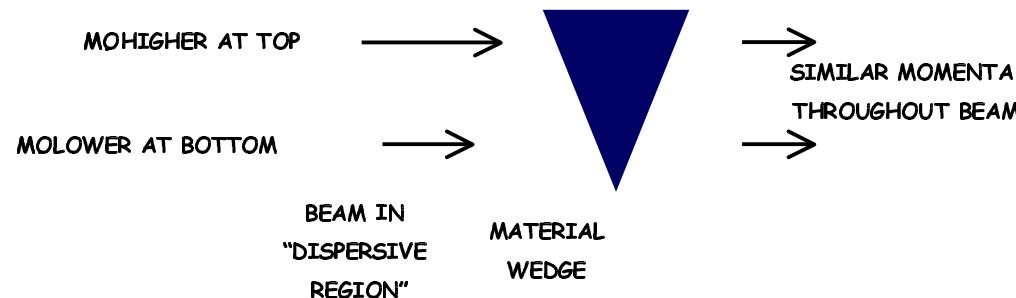
The high-performance ionization cooling channel is the signature technology and dominant technical challenge for muon colliders.

Simple concept:



However, Coulomb scattering and energy straggling compete with cooling,

- A) confines cooling to a difficult region of parameter space (low energy, large angles)
- B) need to control beam energy spread to obtain required $\sim 10^6$ reduction in 6-D phase space:



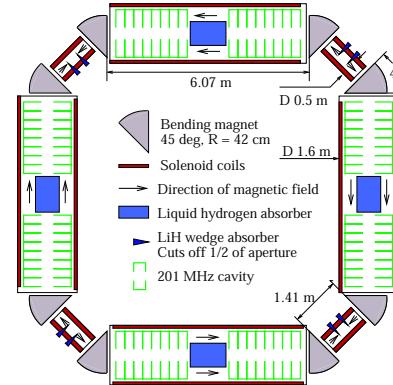
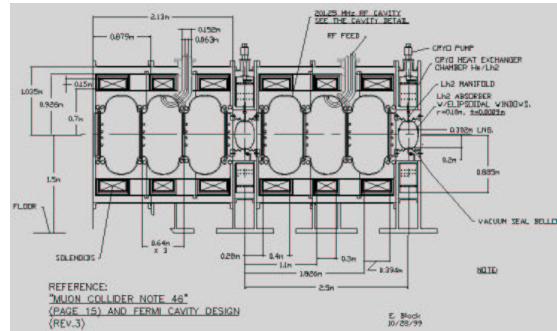
COOLING: WHAT WE HAVE & WHAT WE NEED NEXT



We have:

- a) general theoretical scenarios & specs. to reach the desired 6-D emittances
- b) detailed particle-by-particle tracking codes (modified GEANT, ICOOL) & (new) higher order matrix tracking code (modified COSY-infinity) + (new) wake field code interface
- c) engineering designs of pieces
- d) neutrino factory designs for factor of ~10 *transverse* cooling
- e) "ring cooler" design for MUCOOL expt. with predicted full 6-D cooling by factor of ~32
(c.f. muon collider needs $\sim 10^6 \sim 32^4$)

2 sub-units of a cooling stage (Black, IIT)



"ring cooler"

(Balbekov, FNAL)

But we have yet to put the pieces together to "build the muon collider cooling channel on a computer" => This is our #1 item of business

PROPOSED R&D PROGRAM FOR THE NEXT 2 YEARS



- **priority #1:** "build the muon collider cooling channel on a computer";
10+ FTEs dedicated to muon collider cooling simulations
- **paper studies & simulations** for rest of muon collider, particularly investigations of compatibility with VLHCs and linear e+e- colliders (time-sensitive!)
- **modest hardware program:** restore program for dedicated Li lens R&D;
~few $\times 10^5$ \$/year; may well determine final beam emittance from cooling channel
- hold rigorous but fair **annual reviews**, with the potential for recommendations to progress to a larger R&D program

PREREQUISITE: Muon Collaboration splits into a) Muon Collider Collab. + b) Neutrino Factory Collab.

- in current Muon Collab. plan, muon colliders would receive ~\$0 dedicated R&D funds through FY2006
(ref. M. Zisman presentation to this Panel, slide 20, BNL, April 20, 2001)
- muon collider R&D should be organized by people whose "hearts are in it" (ditto for ν fact.)
- 50-50 split in funding for the first year; subsequent funding based on merit

CONCLUSION: REQUESTS TO PANEL



- 1) please commend the magnificent potential of muon colliders to help HEP, repeating the positive recommendations of your predecessor HEPAP Subpanel (Gilman, 1998):

"The Subpanel recommends that an expanded program of R&D be carried out on a muon collider ..."

- 2) please endorse the R&D program presented here, including:
 - (i) a heavy emphasis on design simulations for a muon collider cooling channel, and
 - (ii) splitting the Muon Collaboration into a) Muon Collider Collab. + b) V Factory Collab., cooperating but separately organized and funded
- 3) colliders at the energy frontier are the most direct & promising experimental route to better understanding the organizing principles of our Universe; please give a strong recommendation for aggressive R&D leading to the construction of cost-efficient collider facilities at the highest constituent energies we can attain.

Thank you!

Table 1: **Self-consistent muon collider ring parameter sets for Snowmass studies.** The final column is the 100 TeV Very Large Muon Collider (VLMC) “straw-man” parameter set and the middle column shows the range of parameters for the straw-man parameter sets assuming a muon collider using acceleration from an existing TeV-scale e+e- linear collider linac (mu-LC). The individual parameter sets for the TESLA and NLC mu-LCs are given individually in the 2 following tables. “Straw-man” means that studies and constructive criticism are invited in order to determine the feasibility or otherwise of the parameter sets. For comparison, the first column displays the range of the corresponding parameters from the muon colliders at 0.1, 0.4 and 3 TeV that are discussed in the paper: The Muon Collider Collaboration, *Status of Muon Collider Research and Development and Future Plans*, Phys. Rev. ST Accel. Beams, 3 August, 1999. The parameters in column 1 that were not provided in that reference have been either estimated or reconstructed for consistency with those parameters that were provided. (B. King; 10 June, 2001)

parameter set center of mass energy, E_{CoM}	MCC Status Rep. 0.1 to 3 TeV	mu-LC 1.6 to 10 TeV	VLMC 100 TeV
collider physics parameters:			
luminosity, $\mathcal{L} [10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}]$	$8 \times 10^{-4} \rightarrow 5.0$	1.0	20
$\int \mathcal{L} dt [\text{fb}^{-1}/\text{year}]$	0.08 → 540	100	2000
No. of $\mu\mu \rightarrow ee$ events/det/year	650 → 10 000	90 → 3400	17
No. of 100 GeV SM Higgs/year	4000 → 600 000	85 000 → 140 000	4.2×10^6
CoM energy spread, $\sigma_E/E [10^{-3}]$	0.02 → 1.1	1.8 → 3.2	0.28
collider ring parameters:			
circumference, C [km]	0.35 → 6.0	3.0 → 10.0	200
ave. bending B field [T]	3.0 → 5.2	5.6 → 10.5	5.2
beam parameters:			
$(\mu^- \text{ or } \mu^+)/\text{bunch}, N_0[10^{11}]$	20 → 40	0.2 → 8	7
$(\mu^- \text{ or } \mu^+)/\text{bunch rep. rate}, f_b [\text{Hz}]$	15 → 30	1 → 650	10
P.S. density, $N_0/\epsilon_{6N}[10^{22} \text{ m}^{-3}]$	1.2 → 2.4	4.0 → 36	0.80
6-dim. norm. emit., $\epsilon_{6N}[10^{-12} \text{ m}^3]$	170	0.10 → 12	88
$\epsilon_{6N}[10^{-6} \text{ m}^3 \cdot \text{MeV}/c^3]$	200	0.12 → 14	104
x,y emit. (unnorm.) [$\pi \cdot \mu\text{m.mrad}$]	3.5 → 620	0.023 → 1.8	0.016
x,y normalized emit. [$\pi \cdot \text{mm.mrad}$]	50 → 290	1.1 → 14	7.6
long. emittance [10^{-3} eV.s]	0.81 → 24	7.9 → 83	530
fract. mom. spread, $\delta [10^{-3}]$	0.030 → 1.6	2.5 → 4.5	0.40
relativistic γ factor, E_μ/m_μ	470 → 14 000	7600 → 47 000	470 000
time to beam dump, $t_D[\gamma\tau_\mu]$	no dump	0.5 → 1.0	no dump
effective turns/bunch	450 → 780	630 → 990	780
ave. current [mA]	17 → 30	0.20 → 7.0	3.5
total beam power [MW]	1.0 → 29	0.81 → 5.5	110
synch. rad. critical E [MeV]	$5 \times 10^{-7} \rightarrow 8 \times 10^{-4}$	$2 \times 10^{-4} \rightarrow 0.02$	0.9
synch. rad. E loss/turn [GeV]	$7 \times 10^{-9} \rightarrow 3 \times 10^{-4}$	$5 \times 10^{-5} \rightarrow 0.03$	13
synch. rad. power [MW]	$1 \times 10^{-7} \rightarrow 0.010$	$4 \times 10^{-4} \rightarrow 0.005$	44
beam + synch. power [MW]	1.0 → 29	0.81 → 5.3	160
power density into magnet liner [kW/m]	1.0 → 1.7	0.012 → 0.50	0.42
interaction point parameters:			
spot size, $\sigma_{x,y} [\mu\text{m}]$	3.3 → 290	0.18 → 1.4	0.36
bunch length, $\sigma_z [\text{mm}]$	3.0 → 140	0.53 → 1.7	8.0
$\beta_{x,y}^*$ [mm]	3.0 → 140	0.53 → 1.7	8.0
ang. divergence, $\sigma_\theta [\text{mrad}]$	1.1 → 2.1	0.13 → 1.4	0.045
beam-beam tune disruption, $\Delta\nu$	0.015 → 0.051	0.010 → 0.100	0.100
pinch enhancement factor, H_B	1.00 → 1.01	1.00 → 1.13	1.11
beamstrahlung frac. E loss/collision	negligible	negligible	1.2×10^{-7}
neutrino radiation parameters:			
collider reference depth, D[m]	10 → 300	100 → 600	100
ave. rad. dose in plane [mSv/yr]	$2 \times 10^{-5} \rightarrow 0.02$	9×10^{-4}	18
str. sec. len. for 10x ave. rad. [m]	1.3 → 2.2	0.63 → 1.0	8.4
ν beam distance to surface [km]	11 → 62	51 → 87	36
ν beam radius at surface [m]	4.4 → 24	1.9 → 6.7	0.075

Table 2: Straw-man collider ring parameter sets for muon colliders using acceleration through the TESLA-800 linac (2001 Technical Design Report parameters), for Snowmass studies. The parameters are for 1 to 5 passes of both muon signs through both linacs, corresponding to 1.6–8 TeV center-of-mass energies. For each parameter set, the worst-case neutrino radiation averaged around the collider plane was fixed at 9×10^{-4} mSv/year, where 1 mSv/year is the U.S. legal limit, and the luminosity was fixed at $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$. (B. King; 10 June, 2001)

collider colliding projectiles center of mass energy, E_{CoM} [TeV]	TESLA e^+e^- 0.8	mu-TESLA				
		$\mu^+\mu^-$ 1.6	$\mu^+\mu^-$ 3.2	$\mu^+\mu^-$ 4.8	$\mu^+\mu^-$ 6.4	$\mu^+\mu^-$ 8.0
collider physics parameters:						
luminosity, \mathcal{L} [$10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$]	5.8	1.0	1.0	1.0	1.0	1.0
$\int \mathcal{L} dt$ [fb $^{-1}$ /year]	580	100	100	100	100	100
R units: no. $\mu\mu \rightarrow ee$ evt./det/year	80 000	3400	850	380	220	140
No. of (115 GeV) SM Higgs/year	$\sim 400 000$	85 000	100 000	120 000	130 000	130 000
CoM energy spread, σ_E/E [10 $^{-3}$]	43 (= δB)	2.5	2.1	2.1	2.0	1.8
collider ring parameters:						
circumference, C [km]	–	3.0	5.0	7.0	8.4	8.7
ave. bending B field [T]	–	5.6	6.7	7.2	8.0	9.6
beam parameters:						
beam energy, E_μ [TeV]	0.4	0.8	1.6	2.4	3.6	4.0
relativistic γ factor, E_μ/m_μ	783 000	7570	15 140	22 710	30 290	37 860
(μ^- or) μ^+ bunch rep. rate, f_b [Hz]	19 544	104	24	7.0	2.3	1.0
(μ^- or) μ^+ /bunch, N_0 [10 11]	0.14	2.0	3.0	4.0	6.0	8.0
P.S. density, N_0/ϵ_{6N} [10 $^{22} \text{ m}^{-3}$]		4.0	4.3	5.2	6.0	6.6
6-dim. norm. emit., ϵ_{6N} [10 $^{-12} \text{ m}^3$]		5.0	7.0	7.7	10	12
ϵ_{6N} [10 $^{-6} \text{ m}^3 \cdot (\text{MeV}/c)^3$]	1.2×10^{-9}	5.9	8.3	9.1	12	14
x,y emit. (unnorm.) [$\mu\text{m.mrad}$]		1.8	0.82	0.48	0.33	0.23
x,y normalized emit. [mm.mrad]		14	12	11	10	8.6
x,y normalized emit. [mm.MeV/c]	$(4000/8) \times 10^{-6}$	1.8	1.3	1.2	1.1	0.9
long. emittance [10 $^{-3} \text{ eV.s}$]	0.5	9.3	16	23	35	57
fract. mom. spread, δ [10 $^{-3}$]	0.6 before coll.	3.5	3.0	3.0	2.8	2.5
time to beam dump, t_D [$\gamma\tau_\mu$]		1.0	0.5	0.5	0.5	0.5
effective turns/bunch		720	630	680	750	910
ave. current [mA]		7.0	1.8	0.75	1.4	0.29
synch. rad. E loss/turn [MeV]		0.05	0.5	2	5	12
synch. rad. power [kW]		0.4	0.9	1	2	3
total beam power [MW]	34	5.3	3.7	2.2	1.4	1.0
decay power into beam pipe [W/m]		500	140	58	32	21
interaction point parameters:						
rms spot size, $\sigma_{x,y}$ [μm]	0.39/0.003	1.4	0.9	0.7	0.6	0.6
rms bunch length, σ_z [mm]	0.3	1.0	1.0	1.0	1.2	1.7
$\beta_{x,y}^*$ [mm]	15/0.4	1.0	1.0	1.0	1.2	1.7
rms ang. divergence, σ_θ [mrad]		1.4	0.90	0.70	0.53	0.37
beam-beam tune disruption, $\Delta\nu$		0.016	0.026	0.040	0.065	0.100
pinch enhancement factor, H_B		1.000	1.000	1.004	1.04	1.13
beamstr. frac. E loss/collision [10 $^{-8}$]		0.009	0.09	0.4	1	2
neutrino radiation parameters:						
collider reference depth, D[m]		200	320	400	450	500
ν beam distance to surface [km]		51	64	71	76	80
ν beam radius at surface [m]		6.7	4.2	3.1	2.5	2.1
max. dose: in-plane ave [10 $^{-3}$ mSv/yr]		0.9	0.9	0.9	0.9	0.9
str. sec. len. for 0.01 mSv/yr max. [m]		1.2	1.1	1.0	0.9	0.8

Table 3: **Straw-man collider ring parameter sets for muon colliders using acceleration through the 1 TeV NLC linac (NLC2001 parameter set B for 2.8 ns bunch spacing), for Snowmass studies.** The parameters are for 1 to 5 passes of both muon signs through both linacs, corresponding to 2–10 TeV center-of-mass energies. (The slightly higher energies than the corresponding TESLA parameters are not significant – 6 passes through the TESLA linac would give 9.6 TeV collisions, etc.) For each parameter set, the worst-case neutrino radiation averaged around the collider plane was fixed at 9×10^{-4} mSv/year, where 1 mSv/year is the U.S. legal limit, and the luminosity was fixed at $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$. The number of particles per bunch in each parameter set has been reduced by approximately a factor of 10 from the approximately corresponding TESLA parameter set because the 11.4 GHz NLC cavities are much smaller than in the 1.3 GHz TESLA design and so cannot transport as much charge per bunch. Some other parameters have been made more aggressive to restore the same luminosity, and so these parameter sets should be considered more speculative than those for TESLA. (B. King; 10 June, 2001)

collider colliding projectiles center of mass energy, E_{CoM} [TeV]	NLC e^+e^- 1.0	mu-NLC				
		$\mu^+\mu^-$ 2.0	$\mu^+\mu^-$ 4.0	$\mu^+\mu^-$ 6.0	$\mu^+\mu^-$ 8.0	$\mu^+\mu^-$ 10.0
collider physics parameters:						
luminosity, \mathcal{L} [$10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$]	1.08	1.0	1.0	1.0	1.0	1.0
$\int \mathcal{L} dt$ [fb $^{-1}$ /year]	108	100	100	100	100	100
R units: no. $\mu\mu \rightarrow ee$ evt./det/year		2200	540	240	140	90
No. of (115 GeV) SM Higgs/year/det.		90 000	110 000	120 000	130 000	140 000
CoM energy spread, σ_E/E [10^{-3}]	81 (= dB)	3.2	2.8	2.6	2.5	2.5
collider ring parameters:						
circumference, C [km]	–	3.6	5.6	7.0	8.7	10.0
ave. bending B field [T]	–	5.8	7.5	9.0	9.6	10.5
beam parameters:						
beam energy, E_μ [TeV]	0.5	1.0	2.0	3.0	4.0	5.0
relativistic γ factor, E_μ/m_μ	978 000	9460	18 930	28 390	37 860	47 320
(μ^- or) μ^+ bunch rep. rate, f_b [Hz]	11 400	650	80	24	10	5
(μ^- or) μ^+ /bunch, $N_0[10^{11}]$	0.082	0.2	0.4	0.6	0.8	1.0
P.S. density, $N_0/\epsilon_{6N}[10^{22} \text{ m}^{-3}]$		20	26	30	33	36
6-dim. norm. emit., $\epsilon_{6N}[10^{-12} \text{ m}^3]$		0.10	0.16	0.20	0.24	0.28
$\epsilon_{6N}[10^{-6} \text{ m}^3 \cdot (\text{MeV}/c)^3]$		0.12	0.18	0.24	0.28	0.33
x,y emit. (unnorm.) [$\mu\text{m.mrad}$]		0.22	0.087	0.053	0.034	0.023
x,y normalized emit. [mm.mrad]		2.1	1.7	1.5	1.3	1.1
x,y normalized emit. [mm.MeV/c]		0.22	0.17	0.16	0.14	0.12
long. emittance [10^{-3} eV.s]		7.9	20	31	50	83
fract. mom. spread, δ [10^{-3}]		4.5	4.0	3.7	3.5	3.5
time to beam dump, $t_D[\gamma\tau_\mu]$		1.0	0.7	0.5	0.5	0.5
effective turns/bunch		750	840	840	910	990
ave. current [mA]		4.6	1.2	0.48	0.29	0.20
synch. rad. E loss/turn [MeV]		0.1	1.1	4.6	12	25
synch. rad. power [kW]		0.5	1.3	2.2	3.4	4.9
total beam power [MW]		4.2	2.1	1.4	1.0	0.81
decay power into beam pipe [W/m]		270	70	29	18	12
interaction point parameters:						
rms spot size, $\sigma_{x,y}$ [μm]	0.24/0.03	0.34	0.26	0.21	0.19	0.18
rms bunch length, σ_z [mm]	0.12	0.53	0.75	0.85	1.1	1.4
$\beta_{x,y}^*$ [mm]	12/0.12	0.53	0.75	0.85	1.1	1.4
rms ang. divergence, σ_θ [mrad]		0.65	0.34	0.25	0.18	0.13
beam-beam tune disruption, $\Delta\nu$		0.010	0.026	0.043	0.067	0.100
pinch enhancement factor, H_B		1.000	1.000	1.007	1.04	1.13
beamstr. frac. E loss/collision [10^{-8}]		0.003	0.03	0.1	0.3	0.6
neutrino radiation parameters:						
collider reference depth, D[m]		240	350	400	500	600
ν beam distance to surface [km]		55	67	71	80	87
ν beam radius at surface [m]		5.8	3.5	2.5	2.1	1.9
max. dose: in-plane ave [10^{-3} mSv/yr]		0.9	0.9	0.9	0.9	0.9
str. sec. len. for 0.01 mSv/yr max. [m]		1.3	1.0	0.8	0.7	0.7